Solar Neutrinos and the Influences of Opacity, Thermal Instability, Additional Neutrino Sources, and a Central Black Hole on Solar Models

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Adoption of the "best" available opacities, of hypothetical additional neutrino sources, or of a central black hole in theoretical models for the sun only increases the discrepancy with the null result of Davis's ^{37}Cl experiment to detect solar neutrinos. No thermal instabilities in any of the solar models have yet been found.

Following the early work of Marx and Menyhard[1] and of Bahcall, Fowler, Iben, and Sears,[2] many investigators have made predictions of the solar neutrino spectrum based on models of the solar interior (see Iben[3] and Bahcall and Ulrich[4] and references therein). All the models that use "standard" assumptions predict approximately the same neutrino spectrum, and variations of these standard parameters are found to introduce relatively minor changes in the predicted neutrino fluxes — at most changes of ~ 2. The current effort by Davis and his coworkers[5] to detect solar neutrinos via the ^{37}Cl experiment has most recently[6] yielded a capture rate of $(0.3 \pm 0.6) \times 10^{-36}\ s^{-1}$ per ^{37}Cl atom, corresponding to a ^{8}B neutrino flux at the earth of $(0.2 \pm 0.4) \times 10^{6}\ cm^{-2}\ s^{-1}$ above the energy threshold of the detector. (The rather high detector threshold means that most of the captured neutrinos are expected to be those from the rare ^{8}B branch in the pp chain.) A reasonable upper limit on the observed flux can be quoted as $\log_{10}\phi(^{8}B) < 5.8$. A recent paper by Ezer and Cameron[7] (hereinafter called Paper I) predicts a typical ^{8}B neutrino flux at the earth of $\log_{10}\phi(^{8}B) = 6.59$. The discrepancy between observation and theoretical prediction has mushroomed with the increased sensitivity of Davis's experiment.

In the present Letter, we examine four significant quantities that affect the internal structure of the sun. Basically, we are here interested in factors that will reduce the temperature near the sun's center. Since the ^8B neutrino loss rate is approximately proportional to T^{13} while the rate of production of usable energy goes like T^4, a small change in T near the center can significantly affect $\phi(^8B)$ while leaving the photon luminosity L essentially unchanged.

Opacity. It is already well known[3,4] that, in theoretical models for the sun, $\phi(^8B)$ increases with the opacity (κ), the initial abundance ratio of helium to hydrogen (Y/X), and the initial abundance ratio of metals to hydrogen (Z/X). Our purpose in reconsidering the opacity is to set improved upper and lower limits on $\phi(^8B)$ by adopting more extreme assumptions about κ and by calculating in detail (1) the pre-main-sequence stages of evolution, starting from the threshold of energy stability, and (2) the approach to equilibrium of the nuclear reactions in the various branches of the pp chain and CNO bi-cycle.

In practice, a reasonable guess is made of the input parameters Y/X, Z/X, and α (the ratio of convective mixing length to pressure scale height). A sequence of stellar models for 1 $M_\odot$ is then evolved up to the present age of the sun (taken to be 4.5×10^9 years), at which point the model ought to have the observed luminosity and radius of the sun; if it does not, revision is made of the three input parameters until agreement is achieved. A loose, additional constraint is provided by the observed abundances of chemical elements in the solar atmosphere, in solar cosmic rays, and in chrondritic meteorites, which seem to require $Y/X \simeq 0.2 - 0.5$ and $Z/X \simeq 0.02 - 0.03$.[7,8] The luminosity is, in general, found to be most sensitive to Y/X and Z/X, while the radius can usually be adjusted by changing α. In the models reported in this Letter, we have adopted (unless otherwise specified) the same basic input physics and method of solution as in Paper I (note that the *pep* reaction has been ignored). The model for the present sun calculated in Paper I will be called the "standard" solar model.

The opacities adopted in Paper I were derived from the Cox-Stewart opacity code for the continuous opacity, and augmented by an approximate correction factor for line absorption, by comparing (1) earlier calculations in which lines were explicitly included[9] and (2) Watson's[10] calculations of line absorption due to auto-ionizing states. However, the electron-scattering opacity (which contributes about one third of the total opacity at the sun's center) was not, and will not be here, reduced by ~30 per cent to account for electron correlations.[11]

An alternative set of continuous and line opacities is the set computed by Carson, Mayers, and Stibbs,[12] who employed the Thomas-Fermi model of the atom instead of the hydrogenic approximation used by Cox and Stewart. In order to make use of these opacities, we have simply multiplied the opacities adopted in Paper I by an approximate factor max $\{1, (3 - |6 - \log T|)\}$. Since Carson *et al.* did not consider temperatures lower than 10^6 °K, the correction factor has been merely assumed to drop off linearly from a maximum value of 3 at 10^6 °K to a value of unity at 10^4 °K, on the grounds that (1) at 10^4 °K, the hydrogenic approximation is satisfactory for the (partially ionized) metals and (2) between 10^4 and 10^6 °K, the relevant part of the solar interior is the small, and mostly adiabatic, outer convection zone (which has little effect on the interior structure). The correction factor probably maximizes the opacities in the solar core if we note that Nikiforov and Uvarov[13] also adopted the Thomas-Fermi atomic model but found opacities closer to those of Cox and Stewart, and that Carson *et al.* assumed a relative abundance of the important contributor neon which is ~10 times higher than current estimates for the sun.[7] (It should be noted, however, that the relative abundances of iron, argon, silicon, etc. are also uncertain, as Watson, Bahcall, and others have emphasized.)

Minimization of the core opacities (except for our omission of electron correlations) is achieved by assuming a pure hydrogen-helium mixture below the photosphere. Physically, this situation is unrealistic because the fully convective Hayashi phase of the early protosun is found to completely homogenize the interior composition (if it is not already homogeneous). But the example is useful as a limiting case.

Results of our calculations for the sun are given in Table I.

TABLE I. Solar neutrino fluxes ϕ (cm^{-2} s^{-1}) at the earth

Case	Standard	Large Opacity	Small Opacity	Black Hole	Black Hole
X	0.762	0.625	0.870	0.762	0.770
Z	0.015	0.015	0.000	0.015	0.015
$M_c/M_\odot$	...	...	...	0.001	0.004
α	1.3	1.1	<0.1	1.3	1.3
X_c	0.43	0.29	0.56	0.32	0.26
T_c(10^6 °K)	15.2	16.9	14.2	15.4	15.8
ρ_c($g\ cm^{-3}$)	147	149	129	223	323
$\log_{10}\phi(pp)$	10.82	10.77	10.84	10.82	10.82
$\log_{10}\phi(^7Be)$	9.50	9.88	9.18	9.51	9.55
$\log_{10}\phi(^8B)$	6.59	7.49	6.04	6.72	6.86
$\log_{10}\phi(^{13}N)$	8.49	9.16	...	8.74	8.62
$\log_{10}\phi(^{15}O)$	8.38	9.14	...	8.69	8.54

With our adopted departures from the standard model, $\phi(^8B)$ is increased by a factor of ~8 for the increased opacity, but reduced by a factor of ~4 for zero metals abundance. This reduction of $\phi(^8B)$ is not significantly smaller than the corresponding reduction factor of 6 found by Bahcall and Ulrich.[4] We should emphasize that $\phi(^8B)$ is very sensitive to the details of calculating the evolutionary sequences (e.g., mass zoning, time steps, convergence criteria, and central convection). All three models for the present sun are found to possess tiny convective cores containing about 0.1 per cent of the total mass.

Central black hole. The sun may contain a relatively massive black hole at its center if interstellar space is populated by gravitationally collapsed objects which act as condensation centers for star formation.[14] It will here be assumed that the radius of such an object with mass M_c is equal to its Schwarzschild radius, $r_S = 2GM_c c^{-2}$; therefore, its gravitational attraction becomes nearly Newtonian beyond a radius of $\sim 10r_S = 10^{-5}(M_c/M_\odot)$ solar units. Since the matter density at this radius in a solar model containing a black hole is expected to be of the same order of magnitude as the central density of a solar model without a central black hole, the mass contained between r_S and $10r_S$ will be only $\sim 10^{-11}\ M_\odot$, which is negligible. Hence we can employ the ordinary (nonrelativistic) equations of stellar structure if we replace the ordinary central boundary conditions by: M_c for the mass, and "effective" values of P_c and T_c for the central pressure and temperature (to be evaluated just outside $10r_S$). We shall ignore questions of the origin of the black hole, of its most likely mass, and of its rate of accretion of surrounding matter, and only evaluate the effect of its supposed presence on $\phi(^8B)$.

Results of calculations using the input physics of Paper I and two values of $M_c/M_\odot$ are shown in Table I. (We have found that a choice of $M_c/M_\odot = 0.010$, and, presumably, larger values, causes the hydrogen to burn up too rapidly to account for the present sun.) Since the "central" gravity is higher for models with a black hole, the core pressures and densities are raised, and this increases the opacity, the temperature gradient, and the central temperature. It therefore follows that $\phi(^8B)$ increases. An interesting sidelight is that the steep density gradient near the center causes the innermost regions to become radiative very early during the pre-main-sequence contraction.

Thermal instability. A fluctuation in the central temperature of the sun will cause an almost immediate fluctuation in the neutrino fluxes received at the earth. But since photons diffuse slowly out of the core, the concomitant fluctuation in nuclear energy generation will cause simply a delayed and damped perturbation of the surface luminosity.[15] Paleontological evidence, at least, rules out any large (>25 per cent) variations of solar luminosity over the past 3×10^9 years.[16] The lowest modes of radial oscillation in the sun are always found to be highly stable (periods of ~ 1 hour, although damping times are of ~ months). Wolff[17] has suggested, however, that major solar flares may excite the sun to high modes of oscillation. But, if so, the induced central temperature fluctuation would probably be extremely small.[18] Sheldon's[19] identification of the 11-year solar cycle with interior hydromagnetic instability does not explain why the core energy source should be pulsing, nor do Shaviv and Salpeter[15] and Fowler[20] try to give a reason for why the central temperature may have reversed its normal evolutionary increase for the past $10^6 - 10^7$ years (thermal diffusion time in the sun), although Fowler hints that the onset of massive convection throughout the sun may have recently taken place for some unexplained reason.

If, however, the sun's nuclear-energy producing region were (cyclically) thermally unstable because of the sensitive temperature dependence of the nuclear reaction rates, this region could be in a temporary temperature minimum at the present time. Although nondegenerate nuclear-burning cores are usually regarded as being thermally stable,[21] it has nevertheless seemed worthwhile to evolve a sequence of solar models using time steps smaller than the e-folding time of thermonuclear runaway, $\sim 10^6$ years. No instability was found in these calculations.[22] Similar results have been obtained by more thorough, but linearized, calculations performed by Schwarzschild[23] and by Aizenman and Perdang.[24]

Apart from the foregoing mechanisms, there remain possible dynamical perturbations induced by convection or rotation in the sun.

Additional neutrino sources. If the sun were emitting copious neutrinos derived from a direct electron-neutrino interaction,[25] the central temperature would be higher than otherwise expected because (1) nuclear energy production must balance both photon and neutrino losses and (2) the speed-up in the rate of evolution would cause the sun to be more highly evolved at its present age of 4.5×10^9 years. In that case, $\phi(^8B)$ would be larger although the copious keV thermal neutrino flux would not be detected in Davis's experiment.

We conclude that the only possibility for reducing $\phi(^8B)$ in the kinds of solar models considered here is a thermal instability of some sort, but we can suggest no plausible mechanism.

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